ELECTROMAGNET HAVING SPACER FOR FACILITATING COOLING AND ASSOCIATED COOLING METHOD

BACKGROUND OF THE INVENTION

1) Field of the Invention

The present invention relates to electromagnets and, more particularly, to an electromagnet having a spacer that defines channels that facilitate cooling of the electromagnet, as well as an associated apparatus and method.

2) Description of Related Art.

Electromagnets are used for various purposes, such as in motors, generators, solenoids, back-up power systems, and transformers. One common application for electromagnets is to provide the actuator mechanism during the installation of rivets or other fasteners, such as in large airframe structures including wing skins, fuselage skins, and the like. Additionally, electromagnets can be used to clamp multiple structures together while drilling or performing a tooling operation on the clamped structures, thereby resulting in a burr-less and debris-free hole. Similarly, an electromagnet may be used to clamp structures together while inserting a rivet or similar fastener to attach the structures. Clamping generally occurs when an electromagnet is positioned adjacent to a structure, and a ferrous material is positioned on the other side of the structure to create a clamping force between the electromagnet and ferrous material.

In most basic principles, the electrical energy input to an electromagnet creates mechanical energy output. Electromagnets generally comprise a coil and ferromagnetic core. The coil generally surrounds the core. As a current is passed through the coil, a magnetic field is created in the vicinity, and the core becomes magnetized and attracts any magnetic material. The force of the magnetic field can be adjusted by changing the number of windings comprising the coil or the amount of current applied to the coil. Electromagnets may be classified as either DC (direct-current) or AC (alternating current), and the type of core depends on which type of current is provided. In either case, as DC or AC is applied to the coil, resistive losses in the coil lead to heat

production. As heat increases, methods for cooling the coil become necessary to remove the excess heat and assure consistent performance. Generally, forced convection and water-cooling are methods used to cool electromagnets.

Specifically, some electromagnet coils are cooled by using a hollow winding and then circulating fluid through the winding. This technique requires high current power supplies and powerful pumps to drive the fluid through a long, narrow passageway. Another technique is bathing the coil in a fluid to conduct heat from the coil to the fluid. Alternatively, layers of the coil may be separated by spacers to facilitate fluid flow, as is most commonly used with large transformers for utility power equipment. The spacers used with electrical utilities are commonly stacked lengthwise along the core and are typically large (about 12 inches in diameter and 12 inches in thickness). However, this technique is not often space efficient and does not offer the degree of cooling that could be provided by a more effective system of fluid circulation about the coils.

It would therefore be advantageous to provide an improved technique for cooling electromagnet coils, such as an improved spacer that is capable of effectively cooling the coils of a magnetized electromagnet. Also, it would be advantageous to provide a spacer that is capable of cooling the electromagnet coils with reduced current and power requirements. Finally, it would be advantageous to provide a spacer that effectively provides coolant to the electromagnet and that is easy to fabricate and install.

BRIEF SUMMARY OF THE INVENTION

The invention addresses the above needs and achieves other advantages by providing an improved electromagnet including a spacer for facilitating cooling of the electromagnet. The spacer includes channels, which facilitate fluid flow along the coil of the electromagnet to provide more effective circulation across the coils. The channels direct fluid both circumferentially and longitudinally along the coil to ensure that the fluid contacts a substantial percentage of surface area on each winding to cool the coil.

In one embodiment, the electromagnet includes a core and at least one winding disposed circumferentially about the core such that the winding extends at least one revolution around the core. The electromagnet further includes at least one spacer having

channels defined therein and disposed circumferentially about the core and adjacent to the at least one winding.

The channels may extend in a generally longitudinal direction along the core, such as with a lattice of diagonally extending channels. Alternatively, the channels may extend in a generally circumferential direction about the core, such as with linked parallel strips. Preferably, there are alternating windings and spacers disposed circumferentially about the core such that each spacer is adjacent to a winding and, more typically, disposed between layers of windings to provide cooling of an adjacent surface of each winding.

The electromagnet may further comprise a first endplate defining an inlet and a second endplate defining an outlet. In addition, a housing may also extend circumferentially about the winding and spacer and between the first and second endplates such that the winding and spacer are enclosed. The first endplate may define channels having a substantially serpentine configuration, thereby defining a path for a coolant medium through the inlet, about the channels defined in the first endplate, through the channels defined in the spacer, and out of the outlet.

In another aspect, an electromagnet includes a core and at least one winding disposed circumferentially about the core such that the winding extends at least one revolution around the core. The electromagnet also includes at least one spacer disposed circumferentially about the core and adjacent to the at least one winding, wherein the spacer defines channels therein. Further, a current source, such as a drill motor, is electrically coupled to the electromagnet, such that the current source is capable of directing current through the at least one winding.

The present invention also provides a method for cooling an electromagnet. The method includes providing an electromagnet having at least one spacer defining channels therein and a coil comprising at least one winding. The electromagnet further includes a first endplate defining an inlet and a second endplate defining an outlet, wherein the first and second endplates are adjacent to opposite ends of a housing such that the coil and spacer are enclosed. Additionally, the method includes magnetizing the electromagnet by providing a current to the coil, and supplying a cooling medium into the inlet defined

within the first endplate and through the channels of the spacer and out of the outlet defined within the second endplate while current is flowing through the winding.

The present invention therefore provides an improved electromagnet and method for cooling an electromagnet. The spacers offer improved circulation of coolant about the coils by distributing the coolant both circumferentially and longitudinally along the coils of the electromagnet. The spacers include different designs for accommodating different coils and impart different cooling properties to the electromagnet. By including a spacer between each winding layer, each winding of the coil will be adjacent to a spacer such that the coil is uniformly cooled. Providing an efficient cooling spacer will in turn increase the efficiency of the electromagnet by reducing heat, as well as reducing the size of the electromagnet.

The electromagnet of the present invention is easily manufactured and is capable of being used for a variety of applications. The spacer may be advantageously machined or molded in a planar state and subsequently wrapped about a coil. Thus, different lengths of spacers are easily machined or molded, and the material used for the spacer provides flexibility for wrapping about the coil and maintaining its shape, as well as not damaging the adjacent windings or coils. In addition, the material chosen for the spacer can be easily sized to match the coil dimensions and does not bunch up or require any adjustments.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

Figure 1 is an exploded perspective view of an electromagnet including a spacer of one embodiment of the present invention;

Figure 2 is a perspective view of one embodiment of a cooling spacer;

Figure 3 is another perspective view of the cooling spacer of Figure 2 showing the cooling spacer as it would wrap circumferentially over a layer of windings;

Figure 4 is a plan view of an alternative embodiment of a cooling spacer;

Figure 5 is a cross-sectional view of cooling spacers and a coil comprising windings wrapped about a core according to one embodiment of the present invention;

Figure 6 is a perspective view of another embodiment of the present invention showing a rivet gun having an electromagnet with a cooling spacer therein; and

Figure 7 is a side view of a synchronized rivet-gun system in accordance with another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

Referring now to the drawings and, in particular to Figure 1, there is shown an electromagnet **10**. The term "electromagnet" is not meant to be limiting, and it is understood that the term electromagnet could be any device that utilizes current passed through revolutions of conductive wire windings wrapped about a core to create a magnetic field about the core, and causing the core to become magnetized when the core is made of a material of high magnetic permeability. The term electromagnet is also meant to apply to any similar device utilizing an air core or other non-permeable material. Thus, the electromagnet could be used in any number of applications, such as in motors, generators, back-up power systems, transformers, clamps, and the like. In addition, the electromagnet could be useful for improving avionics including radar systems utilizing solenoid-based beam power tubes, and possibly to high power density rack-mounted equipment with magnetic devices such as transformers for power supplies and voltage converters.

The electromagnet **10** shown in Figure 1 includes an outer housing **12** and inner housing **14**, as well as endplates **16, 18** that align substantially adjacent to the ends of the outer and inner housings. Each endplate **16, 18** defines an opening **20** and may also define distribution channels **22**. Endplate **16** includes an inlet port **24**, while endplate **18** includes an outlet port **26**. While the inlet port **24** and outlet port **26** denote a direction of fluid flow as described below, the direction of fluid flow may be reversed if desired. A

core **28** is provided that inserts within the openings **20** defined within the endplates **16, 18**, although the core may alternatively be affixed to the end plates in other manners. Generally, alternating layers of spacers **30** and windings **32** (not shown in Figure 1) are wrapped about the core **28** adjacent to one another. Generally multiple windings **32** form a coil **34** (not shown), although the coil could be a single winding. The coil **34**, in turn, is dispersed within the inner housing **14** as shown.

If an AC current is used to energize the electromagnet **10**, the aforementioned components of the electromagnet, except for the coil **34**, are preferably made of a relatively high resistivity material, such as cobalt-iron alloys, iron-nickel alloys, iron-silicon alloys, and the like, and may be laminated (constructed of thin layers) in order to reduce power loss and heating due to eddy currents in the material. In various embodiments of the electromagnet, for example, the high resistivity material may be Hiperco™ material, commercially available from Carpenter Technology Corporation, or Metglass™ material, commercially available from Allied Signal, Inc., although the material could be any similar alloy or like material. When DC current is used, the same materials could be utilized, but the material would not need to be laminated.

The wire comprising the coil **34** may be made of any type of conductive material, such as copper. In addition, the cross-section of the wire may be shaped as desired, such as a square cross-section wire, commercially available from MWS Wire Industries, for ease of winding and/or stacking of windings. In other embodiments, at least a portion of the wire may have a circular, oval, or other cross-sectional shape. The wire that is utilized in winding **32** may be a "magnet wire," as known to those skilled in the art, and may have a relatively thin insulation layer. The insulation may include formvar or polyimide, or a similar coating. Regardless of the type or cross-section of the wire, in some embodiments, 16-gauge wire and lower (larger wire) may conveniently be utilized for ease of winding. For instance, in the embodiments of the electromagnet in which the winding **32** includes 16-gauge wire or larger, a square cross section would provide the best conductive heat transfer in accordance with one embodiment of the present invention, although it is understood that any gauge of wire and cross section could be used.

The core **28** is typically made of a high-permeability material, where the relative permeability of the material is defined as a ratio of the strength of the magnetic field with the material to the strength of the magnetic field without the material. For example, the relative permeability of steel utilized in embodiments of the present invention is typically at least 100. For instance, the core **28** may be made of high-permeability ferrous material, such as 1010, 1018, 1020 low-carbon steel, or the like. In various embodiments of the electromagnet **10**, for example, the core **28** may be made of Hiperco™ 50 material, commercially available from Carpenter Technology Corporation, or any other type of iron cobalt magnetic alloys, and/or carbon steel that has a relatively high saturation flux density and a relatively high permeability.

In some embodiments of the electromagnet **10**, the core **28** may have a circular cross-section, but in other embodiments, the core may have other cross-sections, such as a square-circumferential shape, depending upon the application of the electromagnet. The shape, and in particular, the smallest lateral dimension of the core **18** is optimized to create the maximum amount of flux density, and therefore force, as known to those skilled in the art. In general, the size of the core **28** is optimized when an additional increase in the core size substantially reduces the flux density in the core.

When the electromagnet **10** is energized, the temperature of the coil **34** increases, and the electromagnet **10** may require cooling, at least during times of electromagnet operation. To facilitate cooling, spacers **30** may be placed between the revolutions of winding **32**. Figures 2 and 3 illustrate a spacer **30** of one embodiment of the present invention. The spacer **30** defines a plurality of inner **36** and outer **38** grooves arranged in a mesh pattern. The inner **36** and outer **38** grooves are arranged diagonally, which provide channels for fluid to flow when fluid enters the electromagnet **10**. Thus, the channels direct fluid both longitudinally along the length of the core **28** and circumferentially about the core.

The inner **36** and outer **38** grooves may have various sizes depending, at least in part, upon the capacity of coolant that the grooves are designed to carry. For example, the grooves can be about 0.050 to 0.200 inches in width, in instances where a wire gauge of 18 or larger is used. The spacer **30** can similarly have various thicknesses, such as about 0.050 inches or less in one embodiment. Further, the width and length of the

spacer **30** are generally such that the spacer completely encompasses the underlying winding **32**. Thus, the spacer **30** is advantageously sized to extend substantially between the endplates **16, 18** and circumferentially about the winding **32**.

In another embodiment illustrated in Figure 4, a spacer includes parallel strips **39** extending circumferentially about the coil **34**. The parallel strips may be linked for placement about the coil **34** using several thin strips of tape **40**, or with magnet wire that is fused together into strips using heat. A non-conducting material, such as Kapton™ tape commercially available from E.I. du Pont de Nemours and Company, may be used to connect the parallel strips. Each spacer may include any number of strips per layer, such as approximately 8 to 16 strips per layer, and each strip may have an appropriate width, such as approximately 1/8 to 1/4 inches. The parallel strips are arranged about the core **28** such that the parallel strips extend circumferentially, and as fluid is introduced into the electromagnet **10**, the parallel strips act to distribute the fluid circumferentially.

Although the spacer **30** is shown as having inner **36** and outer **38** grooves and alternatively described as having parallel strips, it is understood that the spacer may include any number of different configurations to ensure that the fluid is distributed about the windings **32** of the coil **34**. For example, the spacer **30** could include radial grooves in a mesh pattern as opposed to diagonal grooves, strips extending substantially longitudinally along each winding **32** as opposed to circumferentially about the core **28**, or other similar type of pattern. It is only required that there be a channel to distribute fluid about the coil **34**, as a solid spacer would inhibit such distribution.

The spacer **30** is preferably manufactured by machining or molding. The spacer **30** may be substantially planar, as shown in Figure 2, prior to machining. The spacer **30** may then have its inner grooves **36** formed by machining parallel grooves, such as to a depth of approximately one half of the material thickness, and subsequently machining a series of similar outer grooves **38**, also to about one half of the material thickness, for example, on the opposite surface of the spacer to create the mesh pattern shown in Figure 2. The spacer **30** may then be easily cut to a desired width and length depending on the width and length of the winding **32** incorporated into the coil **34**. Thus, the sizing and placement of the spacer **30** may be precisely controlled to ensure proper coolant flow through the electromagnet **10**. It is also understood that the spacer **30** could be formed

with a method such as compression molding, injection molding, or similar molding process to manufacture a spacer having inner **36** and outer **38** grooves.

The spacers **30** may be made of any type of material with a high melting temperature that is also, preferably, non-abrasive and non-conductive, such as Teflon™ material, commercially available from E.I. du Pont de Nemours and Company, fiberglass, or a weave material. The spacer **30** is wrapped in a circular configuration when positioned adjacent to the coil **34**, as shown in Figures 3 and 5. Thus, the circumference of the spacer **30** is easily adjusted by properly cutting or otherwise sizing the spacer to accommodate different circumferences of the windings **32** of the coil **34** to ensure that all inner and outer exposed surfaces of each winding **32** are adjacent to a spacer. Therefore, the spacer **30** is advantageously formed of a material that is flexible but stiff enough to maintain its shape about the coil **34**. However, the spacer **26** must not be so stiff as to damage the coating of the underlying winding **32**, as most windings are commonly insulated with a coating such as formvar or polyimide. Although the spacer **30** is shown as having a circular configuration, it is understood that the spacer could be formed into other shapes to extend circumferentially about cores **28** of various cross sections.

Generally for most effective cooling, either one or two layers of windings **32** of wire will be placed between each spacer **30**. Figure 5 illustrates that one layer of winding **32** is adjacent to a spacer **30** on both sides of the winding, with the electromagnet having five windings and three spacers. It is understood that more than two layers of windings **32** could be disposed between spacers **30**, but this design would decrease the cooling capability of the fluid entering the electromagnet **10**, as the windings furthest from the spacer **30**, i.e., those windings not in physical contact with a spacer, will not be cooled as much or as efficiently as those windings that are immediately adjacent to a spacer.

Cooling may occur by circulating fluid around the windings **32** comprising the coil **34** of the electromagnet **10**. Thus, an airflow generator, such as a source of compressed air or another source of coolant, may be connected in fluid communication with the electromagnet **10** in any manner known to those skilled in the art. Alternatively, the fluid may be forced through the electromagnet **10** with a low-pressure pump or the like by pumping fluid through inner housing **14** of the electromagnet **10** that encloses the coil **34** and/or around the coil **34**. The pumping system may cool the fluid, and as the

fluid enters the electromagnet **10**, the electromagnet is cooled. Figure 1 illustrates that fluid may enter the electromagnet **10** at one or more inlets **24**, but the fluid flow may begin at any other appropriate location. Regardless of the type of cool, the fluid utilized to cool the coil **34** may be any type of coolant, such as air, water, glycol, any other type of gas, or other liquid, such as Fluorinert™ coolant, commercially available from the Minnesota Mining and Manufacturing Company.

Figure 1 illustrates one embodiment of a fluid flow path in which the fluid is routed into and through the distribution channels **22** defined in the endplate **16** of the electromagnet. The distribution channels **22** are generally machined into the endplate **16** or backiron, and if these components form part of the magnetic circuit, the machining of the distribution channels will have will have minimal impact on the flux efficiency of the coil **34**. It is understood that the distribution channels **22** may be defined in either endplate **16, 18**, or both concurrently. The distribution channels **22** act to allocate fluid relatively evenly across the entire radial expanse of the coil **34**, and could be any "serpentine" or like configuration to ensure that the fluid is distributed about the coil.

The fluid enters the inlet **24** defined within the endplate **16** and is circulated through the distribution channels **22** to disperse the fluid radially and circumferentially prior to entering the coil **34**. The fluid then enters the coil **34** and is dispersed longitudinally and circumferentially through the spacers **30** due to the mesh pattern defined within the spacer. The fluid acts to cool the windings **36** through convection, as the lower temperature of the fluid acts to draw away heat from the windings **32**. The fluid then exits through the outlet **26** defined within the endplate **18**. The fluid may exit at any other desired location, or may be circulated back to the inlet **24** for further cooling. In the case of air cooled electromagnets, the air may escape into the atmosphere. It is understood that an air generator could be used to force air within the electromagnet **10**, or a pump could be used to force fluid through the electromagnet.

In one embodiment of the present invention, the electromagnet is advantageously adapted for use with a synchronized rivet gun system, as shown in Figures 6 and 7. The rivet gun system advantageously provides a riveting process with reduced noise and improved uniformity of the formed rivets. Figure 6 illustrates that the rivet gun **41** includes a handle **42** and a housing **43**, wherein the housing encloses the electromagnet

10. The rivet gun **41** further includes an electrical socket **44**, optical sensor socket **46**, and a fluid socket **48**. The fluid socket **48** provides an inlet and outlet for coolant entering the electromagnet **10**, while the electrical socket **44** provides a current to the coil **34** to magnetize the core **28**. Figure 7 illustrates two rivet guns **50, 52**, wherein the rivet guns act concurrently to secure two sheets of sheet metal **54, 56** with a rivet **58**. Further details regarding the synchronized rivet gun system are included in U.S. Patent Application No. 10/214,049, filed on August 6, 2002, and entitled "Synchronized Rivet Gun System," which is incorporated herein by reference.

The electromagnet **10** of the present invention is also useful in any number of other applications in which a current source is electrically connected to the electromagnet **10** so as to selectively magnetize the electromagnet. For example, the electromagnet **10** could be used with a clamp for holding large workpieces together or holding a single workpiece in place. U.S. Patent Application No. 10/424,462, filed April 28, 2003, and entitled "An Electromagnetic Clamp and Method for Clamping a Structure," provides additional disclosure on such clamping and is incorporated herein by reference. Other examples of clamps utilizing electromagnets include: U.S. Patent No. 6,357,101 to Sarh et al., a "Method for Installing Fasteners in a Workpiece," and is incorporated herein by reference; and U.S. Patent Publication No. 2003/0221306, filed on May 30, 2002, and entitled "Apparatus and Method for Drilling Holes and Optionally Inserting Fasteners," which is incorporated herein by reference.

Many modifications and other embodiments of the invention set forth herein will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.